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The Chernobyl accident in 1986 - Causes and Consequences

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1 Introduction

At the time of the accident, in the early hours of Saturday 26 April 1986, nearly 200 employees at the Chernobyl nuclear power plant were engaged in the normal operation of Units 1, 2 and 3 and the experiment at Unit 4 that was to lead to the devastating explosion. A further 300 people were were working on the night shift to construct two further reactors (Units 5 and 6) about a kilometre away. At around 01:24 Moscow time, two explosions in quick succession blew the roof off the Unit 4 reactor building, sending concrete, graphite and debris flying and leaving a gaping hole exposing the reactor core to the outside air. Smoke and fumes rose over 1 km into the air, together with a large amount of uranium fuel, transuranics and fission products from the reactor core, including essentially all the noble gases. The heavy material fell out near the site, but lighter particles drifted to the west and north of the plant in a radioactive cloud that contaminated the surface wherever it touched down. The lightest material was carried up by the heat of the explosion to over 1 km in altitude and was blown to the northwest.

2 Initiating events

Chernobyl Unit 4 had operated successfully for three years, with more than 100 reactor years of operation for this RBMK[1] reactor type. The intent on 25-26 April 1986 was to carry out a special electrical systems test just prior to taking the Chernobyl Unit 4 out of service for scheduled maintenance. The purpose of this was to demonstrate improvements in the capacity of the turbine generators to support essential systems during a major station blackout. This was to be done by cutting steam supplies to one of the turbine generators and testing the capacity for supply at correct voltage during its inertial rundown using main coolant flow pumps as the load. The test was intended as a purely electrotechnical one which was thought to have no impact on nuclear safety. As a result, the initiative and direction of the test were left to electrical experts. *Little emphasis was put on nuclear safety, and proper authorizations were not obtained.*

Start of experiment
At 01:00 on 25 April, preparation for the test was begun by the start of power reduction. At 13:05 the reactor power reached 50% (1,600 MW(th)) and turbogenerator No. 7 was shut down. Shortly afterwards the *Emergency Core Cooling System (EECS)* was isolated. The power remained at this level for about 9 hours. At 23:00 power reduction resumed. The generator power was reduced to 700 MW(th) but it proved difficult and the power level dropped to 30 MW(th) and it was only

[1] **R**eaktor **B**olshoy **M**oshchnosty **K**ipyaschiy (Large Power Boiling Reactor).

possible to bring it back to a level of 200 MW(th) by manually withdrawing the control rods. A power level below 700 MW(th) is forbidden for continuous operation due to the *positive power coefficient* for the RBMK reactor below about 20% power level (600 MW(th)). With a positive power coefficient, small changes in power will lead to much larger changes in steam void, with consequent power increases.

Block of shutdown signal

The reactor was operating at 200 MW(th), a level which is forbidden for continuous operation. At 01:19 on 26 April the operators increased feedwater flow and having trouble with pressure and level control, they *blocked the shutdown signals associated with steam drum level and pressure.* When the operator decided that the steam drum level was sufficiently high he sharply reduced the feedwater flow, producing more positive reactivity. The operator received a printout showing that too many control rods were out of the core and that there was not enough reactivity reserve to meet the shutdown requirement. The reactor should at this point have been shut down.

Switch off reactor trip system

At 01:23:04 *the reactor trip on loss of the second generator was switched off and the emergency stop valve to the turbine was closed*. This was done to allow a repeat of the test if needed. This was a *key violation* of the test programme as it was the removal of the last safety system that would have *saved the reactor*.

Prompt criticality

At 01:23:30 the power began to increase. The shift foreman ordered shutdown of the reactor at 01:23:40, but by that time it was too late. There was insufficient reactivity left in the control rods that were in the core, and the others at the top of the core could not be inserted fast enough to counteract the power increase. The positive void coefficient of reactivity inherent in the RBMK design continued to add more reactivity and the prompt critical value was exceeded. The power excursion reached 100 times the full power within four seconds, corresponding to 300,000 MW(th).

Explosion of reactor

An explosion occurred and about 30% of the fuel in the core fragmented, leading to an interaction with water and subsequent steam production. The explosion lifted the 1,000 tonnes core plate with subsequent rupture of *all fuel channels* and the roof of the building was blown off. A second explosion occurred a few seconds after the first explosion, either as a second power excursion or as exploding hydrogen. About 25% of the graphite blocks and material from the fuel channels were ejected through the destroyed roof.

Break out of fire

A fire started in the graphite surrounding the core and also on the roof of the adjoining turbine building and on the roof of Unit 3. Alarms went out to fire units in the region and within minutes plant firemen arrived. None of the firemen had been trained in fighting fires involving radioactive materials. By dawn on Saturday, the more than 100 firemen had succeeded in putting out the roof fires, and about 05:00 all *but* the graphite fire in the core had been extinguished. Firemen, rescue workers and operating personnel were generally unaware of the seriousness of the radiation risk. The high radiation levels could not be measured with available monitoring equipment and in some areas the radiation level must have exceeded 100 $Gy \cdot h^{-1}$. Unit 3 was shut down around 03:00, an hour and a half after the accident, while Units 1 and 2 were not shut down until the following night, about 24 hours after the accident.

3 Radionuclide release and accident management

The Chernobyl accident provides a demonstration of several features of radionuclide releases that had, in the past, been merely predictions and subject to technical controversy. It is now confirmed that extensive releases of radioactive materials can occur in severe reactor accidents. Furthermore, it is clear that the materials can be transported considerable distances from the reactor.

Release of activity

The Chernobyl Unit 4 core contained a radioactive inventory of about $4 \cdot 10^{19}$ Bq (10^{9} Ci) at the time of the accident. On the basis of radiation measurements and various technical analyses of samples taken from a 30 km radius around the Chernobyl plant and throughout the Soviet Union, it has been estimated that about $1\text{-}2 \cdot 10^{18}$ Bq ($3\text{-}5 \cdot 10^{7}$ Ci) of volatiles were released from the fuel during the accident and equal amounts of the noble gases xenon and krypton. The noble gases are thought to have been completely expelled from the fuel. About 10-20% of the volatile radionuclides iodine, caesium and tellurium were expelled from the fuel. Releases of the more refractory radionuclides barium, strontium, plutonium, cerium, etc. amounted to 3-6%. The release of radionuclides did not occur in a single massive event. Rather, only 25% of the release took place during the first day of the accident. The rest of the release took place as a protracted process over a nine-day period. The distribution of activity deposited around the Chernobyl was *0.3-0.5% of the core inventory on-site, 1.5-2% within 20 km,* and *1-1.5% beyond 20 km.* The time distribution of the release is shown at Figure 1.

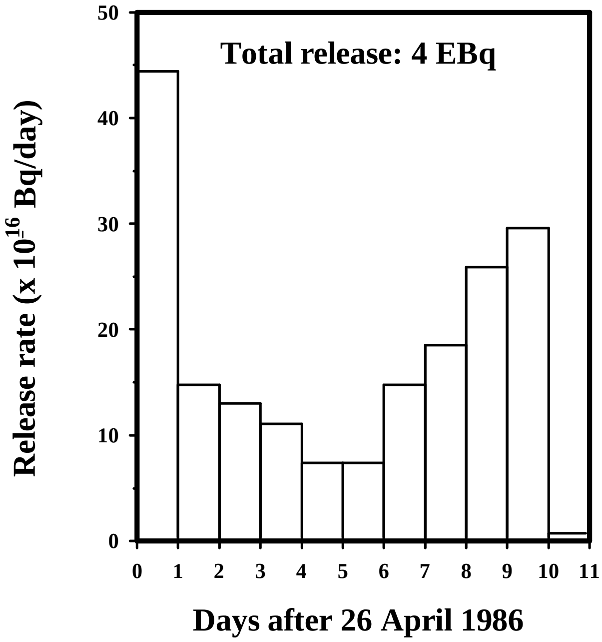

Figure 1. Release of activity from the Chernobyl reactor in the period 26 April to 7 May 1986.

Accident management operations

On 28 April a massive accident management operation began. This involved dropping various materials into the reactor well from helicopters. These included *boron carbide* (B_4C) to ensure against recriticality, *dolomite* ($(MgCa)(CO_3)_2$) to generate carbon dioxide that could provide 'gas blanketing' and could contribute to absorbing the energy of the burning graphite, *clay/sand* to introduce an immediate filtration for radionuclides being released and to quench the fire, and *lead* to absorb heat by melting and to provide a liquid layer that would solidify to seal and shield the top of the core vault. In total, about 5,000 tonnes of materials were dropped into the core vault.

Specialist team from Moscow

The authorities in Moscow were alerted about the accident on 26 April and a specialist team was immediately dispatched to the site to assist local authorities and plant management to deal with the situation. Initially there were some problems in accurately reporting the severity of the accident situation at the plant and off-site.

On their arrival the specialist team found a very serious situation. One of the initial decisions was that a precautionary evacuation of the town of Pripyat should be carried out as soon as possible. On the morning of 26 April, people were instructed to remain indoors with windows and doors shot. To prevent the accumulation of radioisotopes of iodine (mostly ^{131}I) from the plume in the thyroid glands of members of the public, potassium iodide (KI) tablets were distributed to the population of the surrounding zone. This was done employing to hand the tablets to individual residents on a door-to-door basis, starting at the morning of 26 April. Late in the night of 26 April, radiation levels in Pripyat started rising, reaching a value of the order of 10 $mSv{\cdot}h^{-1}$ on 27 April. It was therefore decided to evacuate the city.

Evacuation of the city of Pripyat

Around noon on Sunday 27 April, when the evacuation order had been authorized and all preparations were complete, a short official announcement was broadcast to city residents to pack provisions for three days and to be ready to leave at 14:00. Finally, the nearly 1,200 buses assembled near the settlement of Chernobyl (20 km southeast of Pripyat and 17 km southeast of the plant) set off in a line several kilometres long along the road that passed over the railway just west of Unit 4.

Evacuation of Pripyat began at 14:00. Buses were provided directly at the entrance of each building. As soon as each bus was loaded in front of its assigned apartment building, it set off to join a police escorted line to the reception centres about 50 km away to the west-southwest in Polesskoe and to the south-southwest Ivankov region of the Kiev district. There was adequate transport and the evacuation went smoothly. In less than three hours the city was emptied in orderly fashion of all but those with official duties. The over 44,000 evacuees were taken in by individual families who lived mostly in settlements in the surrounding regions.

Evacuation of 30-km zone

On 28 April, the Civil Defence Chief of Staff of the USSR proposed the evacuation of the Chernobyl plant site and the establishment of a 10 km exclusion zone around the plant. On 2 May, it was decided at a Governmental Commission meeting to evacuate the people from the ’geometric’ 30-km zone around the plant, mainly because of the lack of predictions on the radioactive behaviour under the prevailing meteorological conditions. The evacuation of the entire 30-km zone was completed by 6 May with a total of 115,000 people. The zone remains evacuated, although some people have been allowed to go back to their homes in the less contaminated southern areas.

4 Radiation biology

As ionizing radiation passes through human tissue, it can transfer energy and ionize atoms in cellular molecules that are biologically important for the function of cells. If cellular damage does occur and is not adequately repaired, it may prevent the cell from surviving or reproducing, or it may result in a viable but modified cell. The two outcomes have profoundly different implications for the organism as a whole, leading to socalled *deterministic* and *stochastic* effects. Stochastic effects are effects that occur at random, i.e. that are of statistical nature. Somatic effects, i.e. effects in the exposed individual, and prenatal effects in the embryo can be either deterministic or stochastic. Hereditary effects, i.e. effects in the progeny of the exposed individual, are stochastic.

Deterministic effects

Most organs and tissues of the body are unaffected by the loss of even substantial number of cells, but if the number lost is very large, there will be observable harm reflecting a loss of tissue function. If killed cells are not replaced, an acute effect will be clinically observed in the organism relatively shortly after irradiation. The given level of dose determines whether the effects occur or not, and a direct cause-effect relation can be clinically demonstrated for the irradiated individual. The likelihood of effects is zero at doses lower than some threshold dose and increases steeply to certainty (100%) above such a threshold dose, the severity of the harm is also increasing with dose. Not all cells in the body are equally radiosensitive and typically cells that divide rapidly are more radiosensitive than those that divide slowly or not at all (the reason why cancer cells are more sensitive to radiation than normal cells). Cells that have high sensitivity to radiation include lymphocytes and immature bone marrow. The dose response for the bone marrow syndrome is shown at Figure 2.

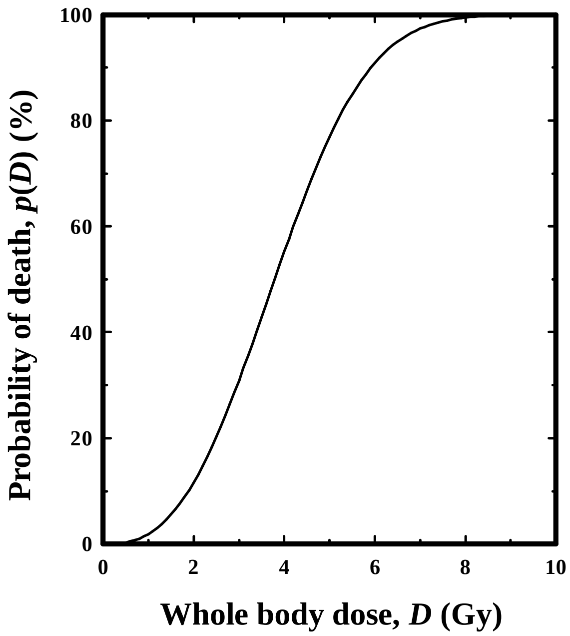

Figure 2. Dose response for acute bone marrow syndrome as a function of absorbed whole body dose[2] given over short time.

It appears from Figure 2 that death is almost certain for an individual incurring a whole body dose of around 6 Gy or more over a short period of time. Doses of around 3 Gy may be lethal for around half of those in an irradiated population who receive little or no medical care (the median lethal dose, LD_{50}). For healthy persons receiving good medical care, LD_{50} may be 5 Gy and as high as 9 Gy with very intensive medical treatment. For doses below 1 Gy the likelihood of

[2] The unit of absorbed dose is Gy (gray). 1 Gy = 1 $J \cdot kg^{-1}$.

deterministic effects is practically zero.

Stochastic effects

The outcome is very different if the irradiated cell is modified rather than killed. Despite highly effective biological defence mechanisms, the cloning of cells resulting from the reproduction of a modified but viable somatic cell may result, after a prolonged and variable time termed latency period, in the manifestation of a malignant condition, *a somatic cancer.*

The probability of a somatic carcinogenesis resulting from radiation is assumed to increase with increments of dose, probably with no threshold of dose below which the probability is zero, and in a way that is roughly proportional to dose, at least for doses well below the thresholds for deterministic effects. The severity of the cancer does not depend on the level of dose.

If the damage occurs in a cell whose function is to transmit genetic information to later generations, any resulting effects, which may be of many different kinds and severities, will presumably be expressed in the progeny of the exposed person as a hereditary effect. Somatic carcinogenesis and hereditary effects are termed *stochastic effects*.

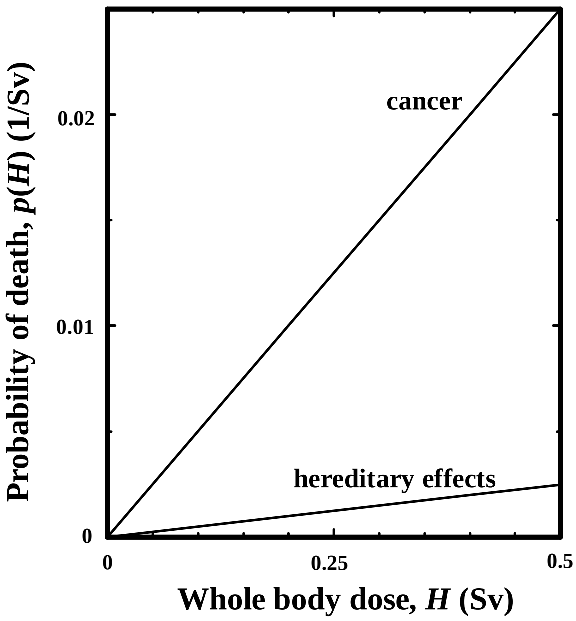

Figure 3. Dose response for stochastic somatic and genetic effects as a function of equivalent whole body dose[3].

According to the current radiobiological theory, the process leading to a stochastic effect can originate at any dose level, however small, the probability of occurrence of an effect being proportional to the incurred dose. This model is termed the *linear, no threshold dose-response relation.* The dose response for stochastic effects is shown at Figure 3 as a function of effective dose.

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[3] The unit of the equivalent dose is the sievert (Sv). 1 Sv = 1 $J \cdot kg^{-1}$. The relation between the absorbed dose, D, and the equivalent dose, H, is $H = w_R \cdot D$. The radiation weighting factor, w_R, accounts for the different effectiveness of cancer induction per unit absorbed dose of different radiation types (α-, β-, γ- and n-radiation) (see Appendix).

Studies of the survivors of the atomic bombings in Japan in 1945 are the most valuable source of information. Since 1947, the Radiation Effects Research Foundation (RERF), jointly funded by the governments of Japan and the USA, has closely monitored the medical health patterns of over 100,000 people who received relatively high doses of whole body radiation. Other large population study groups include some 200,000 persons who received high doses of radiation to specific parts of the body.

Although lifetime data for these groups are incomplete, data from the follow-up period are extensive. In the case of the survivors of the atomic bombings, it is well into its fifth decade. Study findings for these survivors show a statistically significant increase in the frequency of death due to leukaemia as well as to many solid cancers. In total, they show that in addition to the around 20,000 of that population would have been expected to incur cancer from 'natural' causes, around 1,000 incurred cancer that would have been due to doses received as a result of the bombing. Recently, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has updated the risk factors for radiation induced cancer due to a revised dosimetry for the survivors of Hiroshima and Nagasaki, the extended observation period and methodological advances in accounting for different causes of mortality.

Genetic and cytogenetic studies of the nearly 15,000 children born to the atomic bombing survivors in Japan have so far yielded no evidence of a statistically significant increase in severe hereditary defects. UNSCEAR has therefore used two largely independent methods (the doubling dose and the direct method) to estimate the risks to humans of severe hereditary disorders due to radiation induced gene or chromosomal mutations. The latest risk estimates from UNSCEAR on genetic and somatic effects are shown in Table 1.

Table 1. Summary of estimates of probability of stochastic effects of low radiation doses given at low dose rates.

Effect	Population	Probability
Fatal cancers (total)	Workers (18-70 years)	$4{\cdot}10^{-5}$ mSv^{-1}
Fatal cancers (total)	General population	$5{\cdot}10^{-5}$ mSv^{-1}
Severe hereditary effects	First two generations	$1{\cdot}10^{-6}$ mSv^{-1}
Severe hereditary effects	All generations	$5{\cdot}10^{-6}$ mSv^{-1}

5 The International Chernobyl Project

In October 1989, the Government of the USSR formally requested the International Atomic Energy Agency (IAEA) under the United Nations to carry out:

> ".... an international experts' assessment of the concept which the USSR has evolved to enable the population to live safely in areas affected by radioactive contamination following the Chernobyl accident, and an evaluation of the effectiveness of the steps taken in these areas to safeguard the health of the population."

The response from the IAEA was a proposal for a multinational team to undertake an assessment of the radiological situation in the three affected Soviet Republics - the Ukrainian Soviet Socialist Republic (UkrSSR), the Byelorussian Soviet Socialist Republic (BSSR) and the Russian Federated

Socialist Republic (RSFSR).

The *International Chernobyl Project* was thus arranged, with the participation of the Commission of the European Communities (CEC), the Food and Agriculture Organisation of the United Nations (FAO), the International Labour Office (ILO), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Health Organisation (WHO) and the World Meteorological Organisation (WMO). The Project was formalized at a February 1990 meeting in Moscow at the headquarters of the USSR State Committee on the Utilization of Atomic Energy.

Following a fact finding mission through the affected Republics over the period 25-30 March 1990, an International Advisory Committee of scientists from ten countries and seven international organizations was established to direct the Project and be responsible for its findings. Members were called together by international orginasations participating in the Project from well known institutes and universities to represent a spectrum of disciplines, from the radiation specialist to the medical practitioner and the psychologist. This twenty-one member Committee met in Kiev and Minsk from 23 to 27 April 1990 under the chairmanship of Dr. Itsuzo Shigematsu, Director of the Radiation Effects Research Foundation (RERF) in Hiroshima, Japan. The Committee agreed upon a detailed work plan. This would be constrained by a compelling need to complete the Project in one year and by the limitation on the resources available. The Committee would need to rely on the availability of specialized professionals who would volunteer their time.

The International Chernobyl Project was not intended to have the rigour and comprehensiveness of an elaborate long term research study. The intention was to have a multidisciplinary group of international experts critically examine the extensive information, address the key issues and put together an understandable picture of the current situation. The goals of the Project, in short, were to examine assessments of the radiological and health situation in areas of the USSR affected by the Chernobyl accident and to evaluate measures to protect the population.

The work plan adopted called for examining the validity of the official methodologies and findings, and independently verifying them through field samples, laboratory analyses and internationally recognized calculational techniques. The work covered five areas or ’tasks’:

Task 1: Compilation of a historical portrayal of events leading to the current radiological situation

Task 2: Evaluation of the environmental contamination assessments

Task 3: Evaluation of the radiation exposure assessments

Task 4: Assessments of clinical health effects from radiation exposure and evaluation of the general health situation

Task 5: Evaluation of protective measures

The Project selected, in co-operation with local authorities, a number of settlements in the contaminated areas of concern in order to perform the necessary surveys. Settlements were also selected outside the contaminated areas of concern to serve as references for comparative purposes.

The Project was carried out on a completely voluntary basis by a closely co-operating team of some 200 experts associated with research institutes, universities and other organizations in 25 countries and 7 multinational organizations. The time devoted to the Project was volunteered by governments, institutes, companies or the experts themselves. Nearly 50 missions to the USSR were completed between March 1990 and January 1991. The IAEA Laboratory at Seibersdorf along with 13 laboratories in six countries participating on a voluntary basis were involved in the collection and analysis of samples.

The Project received the full support of the USSR Government and the Governments of the BSSR, RSFSR and UkrSSR. Assistance took various forms, including the participation of local scientists in intercomparison exercises, extensive discussions with Project scientists, and assistance in the collection and preparation of field samples and in carrying out medical examinations of the population in the affected areas. There were open and frank conversations with authorities, scientists and especially local citizens that greatly helped the international experts' understanding of the situation.

6 Consequences of the accident within the USSR

The Chernobyl accident involved the largest short term release from a single source of radioactive materials to the atmosphere ever recorded. Aerial radiation measurements and environmental sampling began shortly after the accident and showed that the highest level of environmental contamination was in the area around the reactor that would eventually become the prohibited zone.

Radiation doses in the early stages of the accident

Several groups of people had been exposed to radiation at the Chernobyl power station to such an extent that resulting whole body doses produced various forms of acute radiation syndrome. The groups included operating personnel of the reactor and electricity generating plant, emergency squads and to the largest extent the fire brigades fighting the extensive early fires on the site. Acute radiation syndrome of varying clinical severity was diagnosed in 237 persons, mostly due to external irradiation with gamma and beta radiation. The estimated whole body doses ranged from about *2 Gy up to 16 Gy*. In total, 28 persons died from acute bone marrow failure and of the gastro-intestinal syndrome.

In the first weeks after the accident, the significant radiation exposure to the population was due to the radionuclide ^{131}I. This could have been inhaled from the plume, though that represented only a minor pathway for population exposure. More important were the drinking of milk from cows grazing on contaminated pastures and the consumption of contaminated leafy vegetables. The average absorbed thyroid dose to non-evacuated children were officially reported to be around 2 Gy, with maximum doses up to 30-40 Gy. The distribution of the collective absorbed thyroid doses as officially reported by the Institute of Biophysics in Moscow are shown in Table 2. The collective dose for an exposed population is the sum of all individual doses in the population.

Table 2. Collective absorbed thyroid doses in the three affected Republics.

Republic	Collective dose (man·Gy)	Number of people
Russia	$30 \cdot 10^3$	$705 \cdot 10^3$
Ukraine	$245 \cdot 10^3$	$1{,}277 \cdot 10^3$
Belarus	$561 \cdot 10^3$	$466 \cdot 10^3$
Total	$836 \cdot 10^3$	$2{,}448 \cdot 10^3$

The 115,000 people who were evacuated from the 30 km zone in the early stage of the accident from 28 April to 6 May did receive relatively high levels of whole body dose, although no one developed deterministic effects. Whole body doses were in most cases less than 250 mSv but doses up to 300-400 mSv did occur. The total collective dose to the evacuated people from the 30 km zone has been estimated to 16,000 man·Sv.

At the beginning of the clean up work on the site, most of the workers called in did not have personal dosimeters. These workers, also called 'liquidators', were monitored on a group or area basis, with judgement providing a basis for deciding how much time an individual could spend on a given task or in a given area. In total, 600,000 workers - many from military and Civil Defence - had to be brought in to ensure that no one would exceed the dose limit for emergency workers of 250 mSv used in the USSR at that time. However, about 10% received higher doses in the first days of the accident. It is estimated that the collective whole body dose to the 'liquidators' is about 60,000 man·Sv, corresponding to an average individual dose of 100 mSv.

Radiation doses in the later stages of the accident

Heavy rainfalls combined with local conditions to create 'hot spots' of exceptionally high surface radioactivity levels. Information from continuing aerial surveys and environmental sampling has been used to derive official surface contamination maps which displays the ranges of concentration of caesium, strontium and plutonium. Officially published in 1989, the maps have stirred controversy among scientists and residents. About 25,000 km^2 and 2,225 settlements in the three Republics are officially defined as having surface contamination density in excess of 185 $kBq \cdot m^{-2}$ (5 $Ci \cdot km^{-2}$).

The external exposure due to deposited radionuclides is, in most areas, the most significant contributor to dose, especially in those areas where food restrictions have been applied. Project estimates of doses were made for the surveyed contaminated settlements on the basis of average deposition results. It could not be assumed that such generalized dose estimation assumptions or environmental modelling calculations would accurately reflect the local soil conditions, agricultural practices and living habits in the surveyed contaminated settlements but the results could be expected to provide a general basis for comparison.

Independent Project estimates for the surveyed contaminated settlements were lower than the official reported dose estimates. Overall, there is agreement to within a factor of 2-3 between the independent estimates and the officially reported estimates as shown in Table 3.

Table 3. Individual lifetime effective dose estimates (1986 - 2056) by the International Chernobyl Project compared to official USSR lifetime dose estimates.

Exposure pathway	Project estimate	Official estimate
External exposure	60-130 mSv	80-160 mSv
Internal exposure	20-30 mSv	60-230 mSv
Total	80-160 mSv	150-400 mSv

The collective dose commitment within the affected Republics in the former USSR has been estimated to be 216,000 man·Sv. The distribution of the collective dose on different radionuclides is shown in Table 4.

Table 4. Collective effective dose commitment within the former USSR from the Chernobyl accident distributed on radionuclides.

Radionuclide	Collective dose commitment (man·Sv)
^{137}Cs	155,000
^{134}Cs	43,000
^{131}I	13,000
Short-lived	5,000
Total	216,000

The collective lifetime dose to the population of around 700,000 people living in the most contaminated areas, i.e. in areas with a surface contamination density with ^{137}Cs greater than 185 $kBq{\cdot}m^{-2}$ have been estimated to be 54,000 man·Sv which is about 25% of the total collective dose.

The average lifetime dose to this population group is thus of the order of 100 mSv. With the risk factors given in Table 1 this lifetime dose would correspond to a lifetime risk of fatal cancer of the order of 0.005. For comparison, the lifetime risk of fatal cancer in a society from all causes is around 0.2. Also for comparison, the individual lifetime dose from natural occurring radiation is 150-200 mSv.

Health impact within the USSR

The suspected health impact of the Chernobyl accident has unquestionably been of overriding concern among the population. There had been continuing reports of a higher incidence of illness among those residing in the affected areas. Within the International Chernobyl Project a number of settlements were selected for the medical task force. These settlements were chosen to be representative of the various communities in the study region. The surveyed control settlements had socio-economic structures similar to the seven surveyed contaminated settlements. The aim was to examine various age groups of 20 people each, which, depending on the size of the settlement, represented between 10 and 80 per cent of the population. Approximately, 250 people were examined in each settlement. In all, 1356 people were examined.

There were significant non-radiation-related health disorders in the populations of both surveyed contaminated and surveyed control settlements studied under the Project, but no health disorders that could be attributed directly to radiation exposure. The accident had substantial negative psychological consequences in terms of anxiety and stress due to the continuing and high levels of uncertainty, the occurrence of which extended beyond the contaminated areas of concern.

The children who were examined were found to be generally healthy. Field studies indicated that there were a significant number of adults in both surveyed contaminated and surveyed control settlements with substantial medical problems, with 10-15% requiring medical care.

Reported adverse health effects attributed to radiation have not been substantiated either by those local studies which were adequately performed or by the studies under the Project. Available data reviewed did not provide an adequate basis for determining whether there has been an increase in leukaemia or thyroid cancers as a consequence of the accident. The data were not detailed enough to exclude the possibility of an increase in the incidence of some tumour types. On the basis of the radiation doses estimated by the Project and currently accepted radiation risk estimates, future increases over the natural incidence of all cancers or hereditary effects would be difficult to discern, even with large and well designed epidemiological studies. Reported estimates of absorbed thyroid dose in children are such that there *may be a statistically detectable increase in the incidence of thyroid tumours in the future*.

7 Consequences outside the USSR

Although populations were exposed in the countries of Europe and, to a lesser extent, in countries throughout the Northern hemisphere, the radiation exposures were, in perspective, not of great magnitude. In Denmark, the first-year dose was approximately 0.02 mSv. For reference, the average annual effective dose from natural sources is 2.4 mSv. The first-year doses in different European countries are shown at Figure 4.

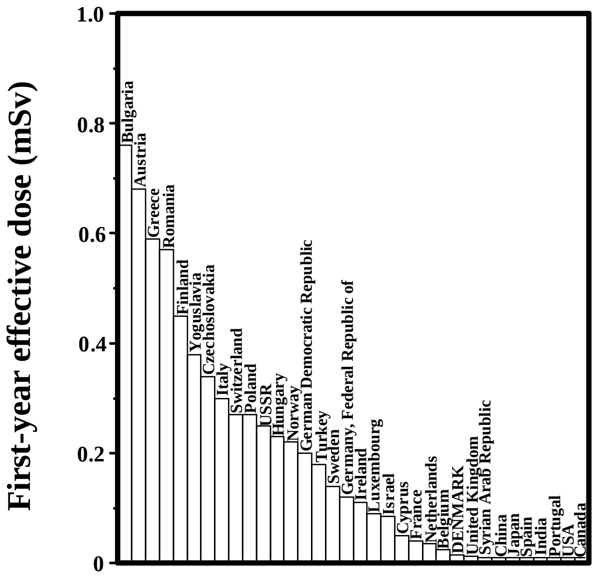

Figure 4. Maximum individual effective doses in different European countries in 1986.

At the time of the accident, surface winds were light and variable, but at 1,500 m altitude the winds were 8-10 $m \cdot s^{-1}$ from the south. At Risø National Laboratory an ionization chamber was measuring the outdoor exposure rate as part of a research project. When the data from the measurement series was read at 28 April, the arrival of the plume at Risø on 27 April was revealed. The ionization chamber continued to measure the increased radiation level above the natural background. On 7 May, heavy rain washed out the radioactive materials still present in the air over Risø. The ionization chamber reading for the period 23 April - 23 June 1986 is shown at Figure 5.

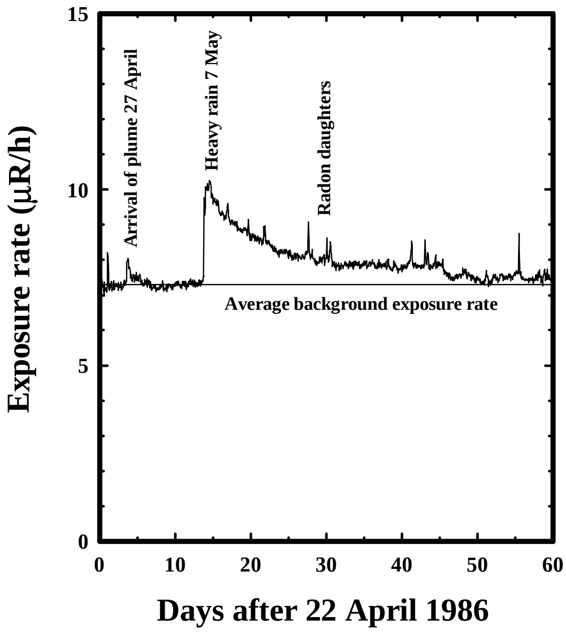

Figure 5. High pressure ionization chamber reading of the outdoor exposure rate at Risø National Laboratory in the period 23 April - 23 June 1986.

Exposures, mainly from ^{137}Cs, will continue for a few tens of years from the external irradiation and ingestion pathways. Estimates of dose commitments have been made by UNSCEAR for larger geographical regions, based on projection models developed from fallout measurements experience. From the ^{137}Cs deposition versus distance relationship, dose estimates for the entire Northern hemisphere have been obtained. The estimated collective effective dose commitment from the accident are shown in Table 5.

Table 5. Collective effective dose commitment outside the former USSR from the Chernobyl accident distributed on areas.

Area outside the USSR	Collective dose commitment (man·Sv)
Europe	318,000
Asia	48,000
Rest of world	18,000
Total	384,000

The collective dose commitment for Europe of 318,000 man·Sv is calculated for a population of 487 million people. The average individual dose commitment can thus be calculated to be around 0.7 mSv, varying between 0.2 and 1 mSv. For comparison, the individual dose commitment from natural sources would be of the order of 200 mSv.

8 Conclusions

The accident at Chernobyl had a societal impact unparalleled in industrial history. The early consequences resulted in the evacuation of more than 100,000 people and involved hundreds of thousands of rescue workers. Vast populations in the Republics of Belarus, Ukraine and Russia continue to live with stress and anxiety due to the lingering uncertainty about the future.

The unprecedented nature and scale of the accident obliged the responsible authorities to respond to a situation that had not been planned for and was not expected. Thus, many early actions had to be improvised. The general response of the authorities in this phase seems to be reasonable and consistent with internationally established guidelines prevailing at the time of the accident.

The protective measures taken or planned for the longer term, albeit well intentioned, generally exceeded what would have been strictly necessary from a radiation protection viewpoint. The relocation and foodstuff restrictions should have been less extensive. It should be recognized, however, that there are many social and political factors to be taken into consideration, and the final decision must rest with the responsible authorities.

There are many important psychological problems of anxiety and stress related to the accident and these seems to be wholly disproportionate to the biological significance of the radioactive contamination. These problems are prevalent even in non-contaminated areas. Review of USSR data indicates that reported cancer incidence rate has been rising since the early eighties and has continued to rise since the accident. The International Chernobyl Project considered that there had been incomplete reporting in the past and could not assess whether the rise is due to increased incidence, methodological differences, better detection and diagnosis or other causes.

The thyroid doses to children are such that there may be a statistically detectable increase in the incidence of thyroid tumours in the future. In fact, there are now indications of thyroid cancers in children induced by the exposure to iodine released from the accident. The type of thyroid cancer is one which would be expected from radiation exposure. On the basis of the radiation doses from the accident and currently accepted radiation risk estimates, future increases over the natural incidence of all cancers or hereditary effects would be difficult to discern, even with large and well designed epidemiological studies. Reported estimates of absorbed thyroid dose in children are such that there *may be a statistically detectable increase in the incidence of thyroid tumours in the future*.

9 References

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Appendix

Radiation dose quantities and units

A1 Absorbed dose

As radiation penetrates any material, its energy is absorbed and released by the constituent atoms. The absorbed radiation energy per unit mass of material is termed the *absorbed dose, D*. The SI unit is the gray (Gy), one gray being equal to one joule energy absorbed per kilogram of matter. The effects of radiation on any material, including biological material such as tissue, depend on the magnitude of the absorbed dose. The absorbed dose can be defined in terms of the related stochastic quantity *energy imparted*, ε. The energy imparted by ionizing radiation to matter of mass, *m*, in a finite volume, *V*, is defined as:

$$\epsilon = (R_{in})_u - (R_{out})_u + (R_{in})_c - (R_{out})_c + \sum Q$$

where $(R_{in})_u$ and $(R_{out})_u$ are the radiant energies (particle energy excluding rest energy) of *uncharged* particles entering and leaving *V*, $(R_{in})_c$ and $(R_{out})_c$ are the radiant energies of *charged* particles entering and leaving *V*, and ΣQ is the net energy derived from rest mass in *V* ($m \rightarrow E$ positive, $E \rightarrow m$ negative). The absorbed dose, *D*, is defined at any point *P* in *V* as:

$$D = \frac{\mathrm{d}\epsilon}{\mathrm{d}m}$$

where ε is now the expectation value of the energy imparted in the finite volume *V*, dε is that for an infinitesimal volume d*V* at point *P*, and d*m* is the mass in d*V*. *Thus the absorbed dose D is the expectation value of the energy imparted to matter per unit mass at a point.*

A2 Radiation weighting factor

Radiation effects, including harm to tissue, are found to depend not only on the absorbed dose, but also on the type and energy of the radiation causing the dose. For radiation protection purposes, these factors are taken into account by weighting the absorbed dose in tissue by a factor related to the relative biological effectiveness of the radiation of causing cancer. The weighting factor for this purpose is termed the *radiation weighting factor*, w_R, and it reflects both radiation type and energy. Radiation weighting factors are shown in Table A1.

Table A1. Radiation weighting factors, w_R, for different radiation types.

Radiation type	Radiation weighting factor, w_R
Photons, all energies	1
Electrons and muons, all energies	1
Alpha particles	20
Neutrons, depending on energy	5 - 20

A3 Equivalent dose

The absorbed dose weighted by the radiation weighting factors is termed the *equivalent dose*, *H*, in a tissue or organ, *T*, is given by the expression:

$$H_T = w_R \, D_{T,R}$$

where $D_{T,R}$ is the mean absorbed dose in tissue or organ *T* due to radiation type *R*. The unit of equivalent dose is the sievert (Sv), where 1 Sv = 1 $J \cdot kg^{-1}$. Equivalent doses are additive regarding the radiation risk of stochastic effects. The equivalent dose is relevant only for doses in the low dose region below the threshold doses for deterministic effects.